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Supersymmetric seesaw model for the (1+3)-scheme of neutrino masses

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ABSTRACT

A four-neutrino spectrum with a sterile neutrino without significant involvement in the atmospheric and solar neutrino oscillation experiments has been recently advocated as the correct picture to explain all existing experimental data. We propose a supersymmetric model in which this picture can be naturally implemented. In this model, the mass for the mainly active neutrino eigenstates is induced by the seesaw mechanism with a large intermediate scale M_R, whereas the mass for the mainly sterile neutrino state is closely related to supersymmetry breaking.

It has been recently proposed to link the mechanism for generating small neutrino masses to the mechanism of supersymmetry breaking [1, 2, 3, 4]. The hierarchy between the gravitino mass $m_{3/2}$ ($\simeq 1\,\mathrm{TeV}$) and the Planck mass M_P ($\simeq 2\times 10^{18}\,\mathrm{GeV}$) induced by the breaking of supersymmetry at $m_X < M_P$, i.e. $m_{3/2}\sim m_X^2/M_P \ll M_P$, make natural the presence of small dimensionless and dimensionful parameters such as $m_{3/2}/M_P$, $m_{3/2}^2/M_P$, as well as $(m_{3/2}\, v)/M_P$ (v is here a typical vacuum expectation value (*vev*) of Higgs doublets), or, generically $\tilde{m}/M_P$ where $\tilde{m}$ is a soft supersymmetry breaking mass. Depending on the value of $m_{3/2}$ and of the soft massive couplings, these parameters may be very important in the neutrino sector, which requires the smallest masses in the spectrum of known particles.

The by now "standard" seesaw mechanism [5, 6] accounts for the lightness of the mainly active neutrino states ν_1, ν_2, and ν_3 in the same way, i.e. making use of a natural suppression factor v^2/M_R, where M_R is an intermediate large scale. This is usually dynamically motivated as the scale of an additional gauge interaction or as the scale of Grand Unified Theories (GUTs). It is generally believed that this mechanism alone is incompatible with an additional light neutrino state with main component sterile, i.e. insensitive to the Standard Model (SM) gauge interactions.

The sterile neutrino needed to simultaneously explain LSND and the solar and atmospheric neutrino experiments [1] is in the range $m_\nu \sim 10^{-4}\,\mathrm{eV}$–$1\,\mathrm{eV}$, if cosmological constraints on neutrino masses [8, 9, 10] are also kept into account. Two four-neutrino pictures exist to describe all the oscillation data. One is the well-known "2+2"picture with two pairs of neutrinos separated by a gap of squared mass $\sim 1\,\mathrm{eV}^2$ ($\equiv \Delta m^2_{\mathrm{LSND}}$) and with the two components of each pair separated by the two squared mass splittings needed for the solar and atmospheric neutrino oscillations, $\Delta m^2_{\mathrm{atm}}$ and $\Delta m^2_{\mathrm{sol}}$ [11, 12]. In particular, it is $\Delta m^2_{\mathrm{atm}} = 10^{-3} - 10^{-2}\,\mathrm{eV}^2$ [11] for the atmospheric neutrino oscillation and $\Delta m^2_{\mathrm{sol}} \sim 10^{-5}\,\mathrm{eV}^2$ or $\Delta m^2_{\mathrm{sol}} = 10^{-9} - 10^{-7}\,\mathrm{eV}^2$, if the MSW oscillation or the quasi-vacuum oscillation are the correct solutions to the solar neutrino problem [13]. This picture requires a large involvement of the sterile neutrino component in the solar neutrino oscillation experiment, which is still marginally allowed by the Super-Kamiokande data [14], although at different levels of confidence in different analyses (cfr. [13] and [14]). The second picture, recently motivated by the smaller oscillation probability now claimed by the LSND experiment [15], is the "1+3" picture with one neutrino heavier than the other three by the amount $|\Delta m^2_{\mathrm{LSND}}|^{1/2}$ [12, 16, 17]. The heavier neutrino is mainly composed by the sterile neutrino; the other three lighter states, mainly active, have masses compatible with any of the two pair of values $(\Delta m^2_{\mathrm{atm}}, \Delta m^2_{\mathrm{sol}})$ given above. This type of spectrum favours small mixing angles between the lighter neutrinos and the heavier one and therefore a marginal involvement of the sterile neutrino in the solar and atmospheric neutrino oscillations.

Light sterile neutrinos can be implemented in the scenarios proposed in Refs. [1] and [4]. Both proposals rely on a specific class of models of supersymmetry breaking [18,

[1]It has been recently pointed out that all existing experimental data on neutrino oscillations can be explained without introducing a sterile neutrino, if CPT is broken [7].

19], based on a supersymmetric $SU(2)$ gauge theory with strong coupling. In these models, a SM singlet Z, with a supersymmetry-breaking *vev* $\mathcal{F}_Z$, acquires also a *vev* $\mathcal{A}_Z$, supersymmetry conserving, but induced by the breaking of supersymmetry [20, 21]. This singlet Z couples to sterile neutrinos via non-renormalizable Yukawa-type interactions, which give rise to small tree-level neutrino masses.

The two proposals, however, differ in some fundamental points. In the first one [1], the only sterile states are the neutrino superfields $\bar{N}$ participating in the generation of masses for ν_1, ν_2, and ν_3. Tree-level Yukawa couplings for the $\bar{N}$ are forbidden by some discrete symmetry under which the relevant superfields are charged. Neutrino masses are generated at the tree level by non-renormalizable operators and radiatively. Both mechanisms, which become possible after the breaking of supersymmetry, induce suppression factors of seesaw type, but in general tend to replace the conventional seesaw mechanism for generating the mass of ν_1, ν_2, and ν_3. The resulting spectra may encompass the typical seesaw spectrum with three heavy Majorana mass eigenstates n_1, n_2, and n_3, if the $\bar{N}$'s are allowed to be heavy, or may be composed of six light eigenstates (ν_i,n_i) for $i = 1, 2, 3$, if the existing discrete symmetries suppress the tree-level mass for the $\bar{N}$ neutrinos. The exact value of masses and mixing angles depends on the specific values of dimensionless couplings and soft supersymmetry-breaking parameters.

In the second mechanism [4], a fourth sterile neutrino superfield S is added to the three heavy right-handed neutrinos, which together with the three active ones, induce Majorana masses for ν_1, ν_2, and ν_3 through the usual seesaw mechanism. The three Majorana states n_1, n_2, and n_3, are at the intermediate scale M_R. The fourth eigenstate ν_s has a mass mainly given by the Dirac mass obtained at the tree-level from the non-renormalizable operator $ZSLH$. Care has to be taken for the coupling of this interaction not to be too large, to avoid instabilities and dangerous vacua lower than the electroweak one. Moreover, R-charges have to be assigned to the relevant fields in order to avoid large radiative contributions to the Majorana mass of active neutrinos. Further discussion on these aspects can be found in Ref. [22]. The light eigenstate ν_s, of Dirac type, has a mass of order $10^{-4}\,\text{eV}$, i.e. the mass required for the solar neutrino quasi-vacuum oscillation. For m_{ν_2} and m_{ν_3} of order $0.1\,\text{eV}$, and m_{ν_1} also of order $10^{-4}\,\text{eV}$, which can be easily disposed for by the seesaw mechanism, this spectrum is consistent with the "2+2" picture of neutrino masses.

Motivated by the new LSND claim and the analysis of Refs. [16, 17], we try now to build a model in which the "1+3" picture can be accommodated. As in the proposal of Ref. [4], we assume the usual seesaw mechanism to be the one inducing small values of m_{ν_1}, m_{ν_2}, and m_{ν_3} and only one sterile neutrino S is added to the three heavy $\bar{N}$'s. Once again, the mechanism for generating m_{ν_s} is linked to supersymmetry breaking, but differently than in the proposals of Refs. [1] and [4], it is independent of the specific realization of this breaking.

Seven neutrino chiral superfields are present in this model: the three neutral components of the leptonic doublets L_α, with $\alpha = e, \mu, \tau$, the three superfields $\bar{N}_\alpha$, and S.

A continuous $U(1)_R$ symmetry, which is known to be important for the solution of the μ problem [23], is assumed. Under this symmetry the relevant SM fields and the sterile neutrino S have the following R-charges:

$$R(L_\alpha) = 1, \quad R(\bar{N}_\alpha) = 1, \quad R(H) = 0, \quad R(\bar{H}) = 0, \quad R(S) = -1\,. \tag{1}$$

Tree-level Yukawa interactions for the sterile neutrino S are consequently forbidden. The superpotential allowed by this symmetry can then be decomposed as:

$$W = W_0 \,+\, W_1 \,+\, W_2\,. \tag{2}$$

W_0 collects the usual SM Yukawa operators. W_1 contains mass and interaction terms for the right-handed neutrinos $\bar{N}$:

$$W_1 = y_{\alpha\beta}\bar{N}_\alpha L_\beta H \,+\, \frac{1}{2} M_{R\,\alpha\beta}\bar{N}_\alpha\bar{N}_\beta\,, \tag{3}$$

where $M_{R\,\alpha\beta}$ are the typical large seesaw masses. Finally, W_2 contains all mass and interaction terms for S, together with an operator giving rise to the bilinear $\mu H\bar{H}$ term:

$$W_2 = h_H H\bar{H}\frac{\langle W\rangle}{M_P^2} \,+\, f_\alpha \bar{N}_\alpha S\frac{\langle W\rangle}{M_P^2} \,+\, k_\alpha S L_\alpha H\frac{\langle W\rangle}{M_P^3} \,+\, \frac{1}{2}hSS\frac{\langle W\rangle^2}{M_P^5}\,. \tag{4}$$

$\langle W\rangle$ is here a constant term of the superpotential. It carries R-charge *two* and has value $m_{3/2}M_P^2$ in order to cancel the vacuum energy density arising from the supersymmetry breaking sector [24]. Notice that the mixed mass terms $\bar{N}_\alpha S$, as the bilinear Higgs term $H\bar{H}$, are naturally at the scale $m_{3/2}$. They give rise to mixed fermion mass terms $\bar{\nu}_{R\,\alpha}\nu_{Ls}$ and $\bar{\nu}_{Ls}\nu_{R\,\alpha}$ for right-handed and sterile neutrino current eigenstates, where ν_{Ls} and $\nu_{R\,\alpha}$ are respectively the fermionic component of S and the charged conjugated fermionic components of the superfields $\bar{N}_\alpha$. As usual, the fermionic components of the neutrino superfields in the doublets L_α are denoted by $\nu_{L\alpha}$. (It is understood here that the charged lepton fields are in the basis in which their mass matrix is diagonal.)

Thus, on the basis $\{\nu_{Ls}, \nu_{L\alpha}, \nu^c_{R\alpha}\}$, the 7×7 neutrino mass matrix gets the form:

$$\left(\begin{array}{c|cc} h\epsilon m_{3/2} & \mathsf{k}^T\epsilon v & \mathsf{f}^T m_{3/2} \\ \hline \mathsf{k}\epsilon v & \mathbf{0} & \mathbf{y}^T v \\ \mathsf{f} m_{3/2} & \mathbf{y}v & \mathbf{M_R} \end{array}\right), \tag{5}$$

when a matrix notation is adopted: $\mathbf{M_R}$ and $\mathbf{y}$ are 3×3 matrices in generation space, f and k are 3-component vectors. The dimensionless parameter ϵ is the ratio $m_{3/2}/M_P$. In the limit $\epsilon \to 0$, this matrix is of rank *six* and one eigenvalue vanishes identically. The actual neutrino spectrum can be easily read from the mass matrix for the four light neutrinos, obtained by integrating out the three heavy ones, of mass $\sim M_R$. This 4×4 mass matrix has the form:

$$-\left(\begin{array}{c|c} \mathsf{f}^T\frac{1}{\mathbf{M_R}}\mathsf{f}\, m_{3/2}^2 - h\epsilon m_{3/2} & \mathsf{f}^T\frac{1}{\mathbf{M_R}}\mathbf{y}\, m_{3/2}v - \mathsf{k}^T\epsilon v \\ \hline \mathbf{y}^T\frac{1}{\mathbf{M_R}}\mathsf{f}\, m_{3/2}v - \mathsf{k}\epsilon v & \mathbf{y}^T\frac{1}{\mathbf{M_R}}\mathbf{y}v^2 \end{array}\right). \tag{6}$$

The spectrum of light neutrinos is then composed of two states, ν_2 and ν_3, with mass $\sim (yv)^2/M_R$; one, ν_s, at the scale $\sim (f m_{3/2})^2/M_R$, and one, ν_1, with much smaller mass $\sim v^2/M_P$. Since $m_{3/2}$ is in general expected to be larger than the electroweak scale ($v \simeq \mathcal{O}(100)\,\mathrm{GeV}$) by roughly one order of magnitude, the hierarchy in the "1+3" scheme between m_{ν_s} and the heavier of the two states ν_2 and ν_3, say ν_3, is naturally obtained. For $M_R \sim 10^{15}\,\mathrm{GeV}$, it is $m_{\nu_s} \sim 1\,\mathrm{eV}$ and $m_{\nu_3} \sim 10^{-2} - 10^{-1}\,\mathrm{eV}$. Without much tuning of the couplings y and the masses M_R, the lighter state in this pair can then be given a mass $m_{\nu_2}^2 \sim \Delta m_{sol}^2$. For the MSW solution to the solar neutrino problem, m_{ν_2} needs to be only about one order of magnitude smaller than m_{ν_3}.

Furthermore, it is easy to see from the matrix (6), that the mixing angles between the sterile neutrino and other three active neutrinos is of order of $v/m_{3/2} \sim 0.1$, which is the correct order of magnitude for the "$1+3$" scheme. This implies, together with $m_{\nu_s} \sim 1\,\mathrm{eV}$, that the neutrino mass term $m_{\nu_e\,\nu_e}$ contributing to the 2β decay is in a range of 10^{-2}–$10^{-3}\,\mathrm{eV}$, which is accessible to the future 2β decay experiments [25].

The intermediate scale M_R can be dynamically explained as the breaking scale of an additional gauge symmetry. The simplest candidate for this gauge symmetry is $U(1)_{B-L}$, where B and L are the baryon and the lepton number, respectively. Given the presence of the sterile neutrino superfield S, another sterile neutrino superfield $\bar{N}_o$ needs to be added, in order to cancel $U(1)_{B-L}$ gauge anomalies. The gauge symmetry is broken by two chiral multiplets Φ and $\bar{\Phi}$ carrying nonvanishing $U(1)_{B-L}$ charges. The $U(1)_{B-L}$ charges for the fields L_α, H, $\bar{H}$, $\bar{N}_\alpha$ is uniquely fixed (up to a $U(1)_Y$ transformation) by the requirement of exactly vanishing gauge anomalies as follows:

$$X(L_\alpha) = -1, \;\; X(H) = 0, \;\; X(\bar{H}) = 0, \;\; X(\bar{N}_\alpha) = +1\,; \tag{7}$$

we choose those for $\bar{N}_o$, S, Φ, and $\bar{\Phi}$ to be:

$$X(\Phi) = +2, \;\; X(\bar{\Phi}) = -2, \;\; X(\bar{N}_o) = +1, \;\; X(S) = -1\,. \tag{8}$$

Finally, we assign R-charges to the additional superfields $\bar{N}_o$, Φ, and $\bar{\Phi}$ according to the standard prescription for fermionic matter and Higgs superfields:

$$R(\bar{N}_o) = 1, \quad R(\Phi) = 0, \quad R(\bar{\Phi}) = 0\,. \tag{9}$$

(Notice that the quantum numbers for the additional $\bar{N}_o$ are the same as those for $\bar{N}_\alpha$.) The two terms W_1 and W_2 in the superpotential are now modified as follows. W_1 has the form:

$$W_1 = y_{\alpha\beta}\bar{N}_\alpha L_\beta H \,+\, y_{o\alpha}\bar{N}_o L_\alpha H \,+\, \frac{1}{2} z_{\alpha\beta}\bar{\Phi}\bar{N}_\alpha\bar{N}_\beta \,+\, z_{o\alpha}\bar{\Phi}\bar{N}_o\bar{N}_\alpha \,+\, \frac{1}{2} z_{oo}\bar{\Phi}\bar{N}_o\bar{N}_o\,, \tag{10}$$

where

$$z_{\alpha\beta}\langle v_{\bar{\Phi}}\rangle = M_{R\,\alpha\beta}, \quad z_{o\alpha}\langle v_{\bar{\Phi}}\rangle = M_{R\,o\alpha}, \quad z_{oo}\langle v_{\bar{\Phi}}\rangle = M_{R\,oo}\,. \tag{11}$$

W_2 is modified to include an additional operator mixing the superfields $\bar{N}_o$ and S, and to have a more suppressed form for the last two operators:

$$W_2 = h_H H\bar{H}\frac{\langle W\rangle}{M_P^2} + f_\alpha \bar{N}_\alpha S\frac{\langle W\rangle}{M_P^2} + f_o\bar{N}_o S\frac{\langle W\rangle}{M_P^2} + k_\alpha \Phi S L_\alpha H\frac{\langle W\rangle}{M_P^4} + \frac{1}{2} h\Phi S S\frac{\langle W\rangle^2}{M_P^6}\,, \tag{12}$$

as required by the $U(1)_{B-L}$ charge assignment (7) and (8).

Again, going to a matrix notation, the 8×8 neutrino mass matrix for the eight states $\{\nu_{Ls}, \nu_{L\alpha}, \nu^c_{R\alpha}, \nu^c_{Ro}\}$ is now:

$$\left(\begin{array}{c|ccc} h\epsilon\epsilon' m_{3/2} & \mathsf{k}^T\epsilon\epsilon' v & \mathsf{f}^T m_{3/2} & f_o m_{3/2} \\ \hline \mathsf{k}\epsilon\epsilon' v & \mathbf{0} & \mathbf{y}^T v & \mathsf{y_o} v \\ \mathsf{f} m_{3/2} & \mathbf{y} v & \mathbf{M_R} & \mathsf{M_R} \\ f_o m_{3/2} & \mathsf{y_o}^T v & \mathsf{M_R}^T & M_R \end{array}\right), \tag{13}$$

where, with an abuse of notation, the same symbol is used to indicate a 3×3 matrix $\mathbf{M_R}$, a 3-component vector $\mathsf{M_R}$, and a 1-component number M_R. The symbol $\mathsf{y_o}$ indicate the 3-component vector collecting all couplings $y_{o\alpha}$, and ϵ' is the additional suppression factor $\langle v_{\bar{\Phi}} \rangle / M_P$. In this case, differently from the case without $\bar{N}_o$, the rank of the matrix remains the maximal one, i.e.*eight*, even in the limit $\epsilon\epsilon' \to 0$. Once the heavy states are integrated out, the 4×4 mass matrix for the light states is formally of the same type as the matrix in eq. (6). Its exact form is:

$$-\left(\begin{array}{c|c} \left(\mathsf{f}^T,\, f_o\right) \dfrac{1}{\mathcal{M}} \begin{pmatrix} \mathsf{f} \\ f_o \end{pmatrix} m^2_{3/2} - h\epsilon\epsilon' m_{3/2} & \left(\mathsf{f}^T,\, f_o\right) \dfrac{1}{\mathcal{M}} \begin{pmatrix} \mathbf{y} \\ \mathsf{y_o}^T \end{pmatrix} m_{3/2} v - \mathsf{k}^T \epsilon\epsilon' v \\ \hline \left(\mathbf{y}^T,\, \mathsf{y_o}\right) \dfrac{1}{\mathcal{M}} \begin{pmatrix} \mathsf{f} \\ f_o \end{pmatrix} m_{3/2} v - \mathsf{k}\epsilon\epsilon' v & \left(\mathbf{y}^T,\, \mathsf{y_o}\right) \dfrac{1}{\mathcal{M}} \begin{pmatrix} \mathbf{y} \\ \mathsf{y_o}^T \end{pmatrix} \end{array}\right), \tag{14}$$

where the matrix $\mathcal{M}$ is the 4×4 matrix of heavy masses:

$$\mathcal{M} = \begin{pmatrix} \mathbf{M_R} & \mathsf{M_R} \\ \mathsf{M_R}^T & M_R \end{pmatrix}. \tag{15}$$

The mass spectrum and the mixing angles are similar to those obtained in the case without $\bar{N}_o$, although in this case m_{ν_1} is not suppressed with respect to m_{ν_2} and m_{ν_3}.

Notice that, because of the large scale M_R, no large radiative contributions to neutrino masses, as those described in Ref. [1], can arise. Moreover, given the $U(1)_{B-L}$ and the $U(1)_R$ charge assignments, trilinear contributions to the scalar potential, involving the scalar component of the superfield S, $\tilde{S}$, as well as the bilinear term $B_S\tilde{S}\tilde{S}$ are suppressed. Therefore, also radiative contributions mediated by $\tilde{S}$ [22] do not alter the tree-level spectrum given above.

This model may be easily extended to a GUT scheme, with gauge group $SU(5)_{\rm GUT} \times U(1)_5$. The additional $U(1)_5$ is the so-called fiveness. By breaking $SU(5)_{\rm GUT} \times U(1)_5$ down to the SM, one ends up with the group $SU(3) \times SU(2) \times U(1)_Y \times U(1)_{B-L}$, where $B - L$ is given by a linear combination of the fiveness Y_5 and hypercharge Y:

$$B - L = \frac{1}{5} Y_5 + \frac{4}{5} Y. \tag{16}$$

The usual quarks, leptons and neutrinos $\bar{N}_\alpha$ transform as $(\mathbf{5}^*, -3)$, $(\mathbf{10}, +1)$, and $(\mathbf{1}, +5)$, while the additional $\bar{N}_o$ and the sterile neutrino S as $(\mathbf{1}, +5)$ and $(\mathbf{1}, -5)$. Here the

numbers in the parentheses denote the dimensions of $SU(5)_{\rm GUT}$ representations and the fiveness Y_5 charges. However, a further unification to a $SO(10)$ or E_6 model seems difficult, due to the presence of the two additional fields $\bar{N}_o$ and S. One may consider that the presence of these additional fields is explained by more fundamental theories (e.g., superstring theories) beyond GUTs.

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